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Tunable terahertz refractive index sensor based on flexible thin-film elliptical split-ring resonator for Gas sensing application

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Background & Aim

In recent years, the demand for sensitive and reliable gas sensing technologies has surged due to environmental concerns and the need for safety in various industrial applications. Terahertz (THz) sensing has emerged as a promising technique due to its unique ability to probe molecular vibrations and rotational transitions, providing valuable information about the composition of gases. Among the various structures utilized in THz sensing, split-ring resonators (SRRs) have gained attention for their ability to enhance electromagnetic field interactions with the target gas, leading to improved sensitivity and selectivity. Flexible thin-film materials have also opened new avenues for sensor development, allowing for the integration of sensors into wearable devices and other unconventional substrates. The combination of flexibility and the unique resonant properties of elliptical SRRs enables the design of tunable sensors capable of adapting to different environmental conditions and sensing needs.

In this paper, a plasmonic resonator for Gas sensing application in the terahertz (THz) region, which consisted of metal elliptical split-ring resonator array based on Polymer flexible thin-film, was proposed and verified numerically. The proposed structure consists of a split-ring made of gold on a layer of polymer. Polymer is a flexible and recyclable material in nature. Three polymers Poly methyl methacrylate (PMMA), Parylene-c and Polycarbonate (PC) have been investigated in this article as the substrate of the structure. The ring width and gap width parameters of the elliptical split ring resonator are investigated on how they affect the performance of the flexible gas sensor.

Methodologies

As shown in Fig. 1(a), a unite cell of flexible metamaterial gas sensor was designed in the THz regime. The proposed metamaterial structure consists of a metal layer (elliptical ring with a split (gap) width size of g) and a flexible substrate layer made of polymer. As can be seen from this figure, the terahertz waves radiate perpendicularly to the metal ring and after passing through the structure (after reacting with the refractive index of the medium where the sensor is placed in it), it is detected by the detector at the end of the substrate. The gas under measurement is placed in the vicinity of the elliptical split-ring made of gold as shown in Fig. 1(b). The elliptical split-ring had major axis size a, short-axis size b, ring width e, gap width g, and thickness of gold film 100 nm. The original geometric parameters of metamaterials were set as a=20µm, b=14µm, e=4µm, g=2µm, c=30µm, d=24µm. The substrate layer is a flexible polymer layer, which has a thickness of 20µm. In this article, we have used three polymers: parylene-c (n=1.658) [8], PMMA and PC. The dispersion relations for PMMA and PC are obtained from the sellmeier equation and from the following relation:

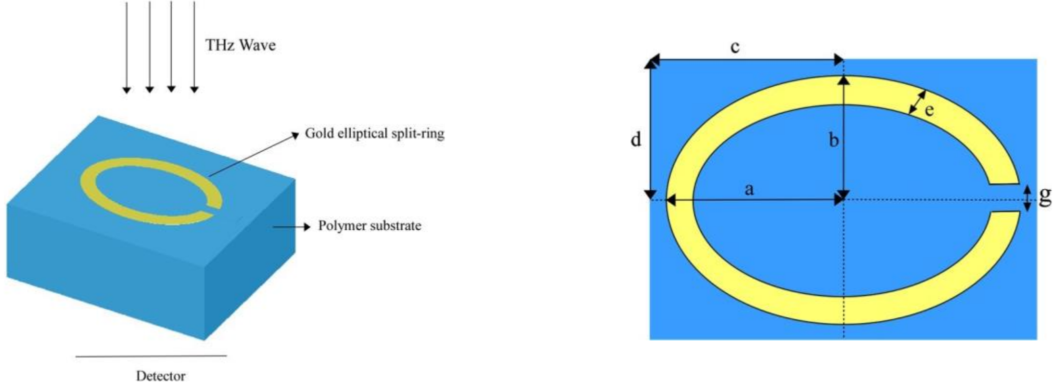
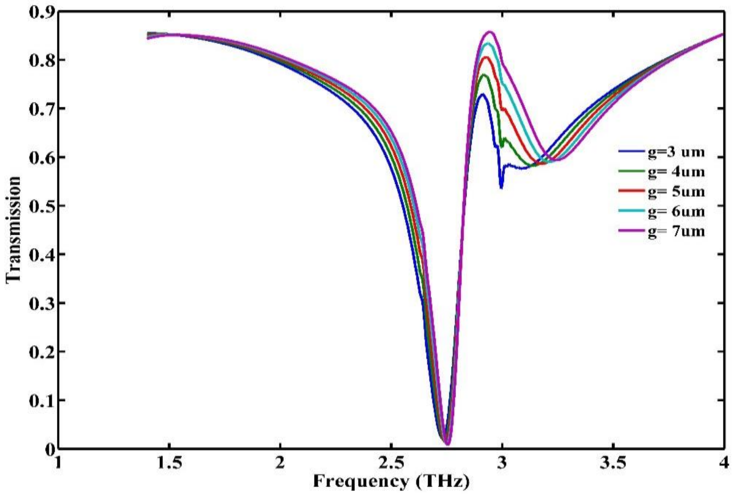


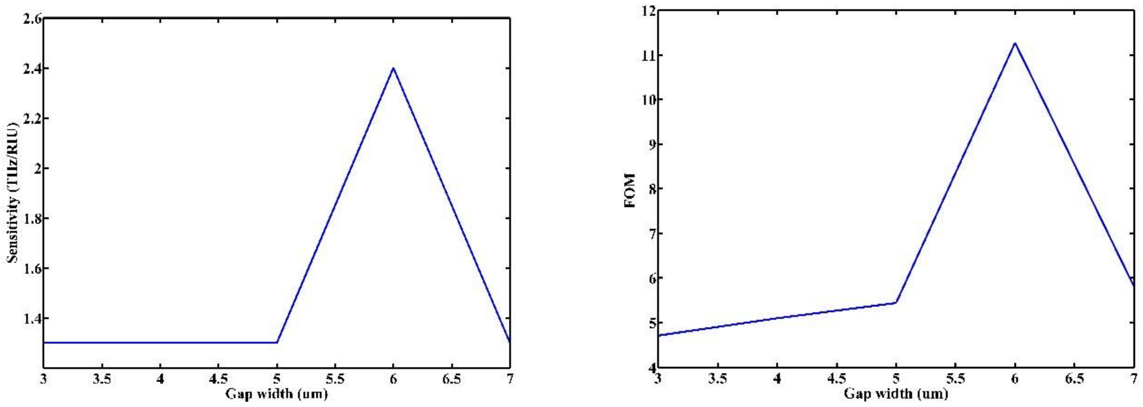
Fig.1. Schematic diagram of the unite cell of flexible metamaterial structure. (a) Metamaterial gas sensor; (b) The unit cell of the 2D split elliptic resonance ring.

Results

In the proposed sensor, changing the geometrical parameters related to the gap width affects the performance of the transmission and sensing spectrum. In order to obtain better sensing performance, we investigate the gap width change and its effect on the sensing performance. In order to investigate the change process of the transmission spectrum, we change the width of the gap in the range of 3µm to 7µm with steps of 1µm. During this change, other geometric parameters remain unchanged and at their initial value (a=20µm, b=14µm, e=4µm, c=30µm, d=24µm). Also, the substrate is made of Parylene-c material. We consider the refractive index of the outside environment to be pure air with its refractive index n=1. As shown in Fig. 2(a), the resonance dip of the transmission spectrum experiences a red shift with increasing gap width.



(a)



(b) (c)

Fig. 2: Simulated transmission spectra of the variations of metamaterial gap width versus frequency. (a) Changing of the different transmitted spectra with the gap width; (b) Sensitivity changing with the gap width; (c) FOM changing with gap width.

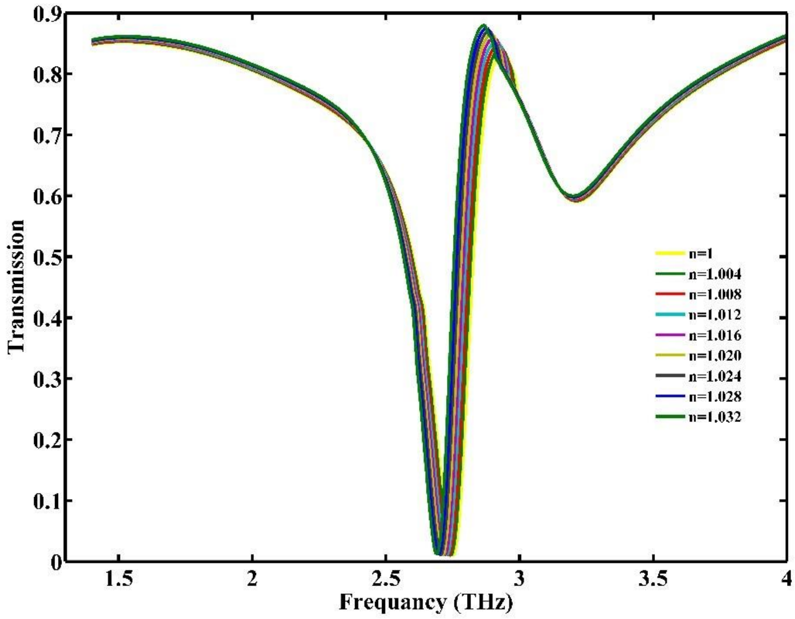
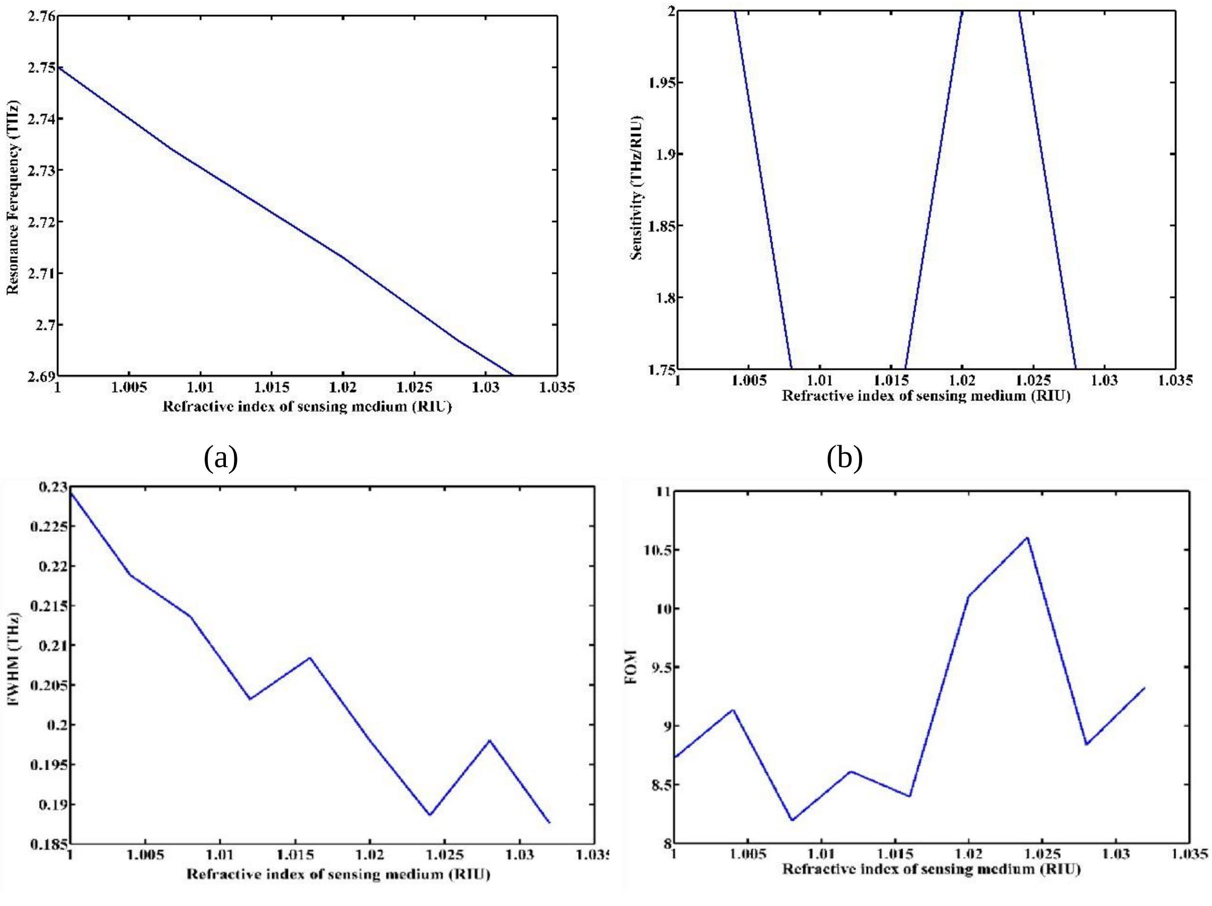


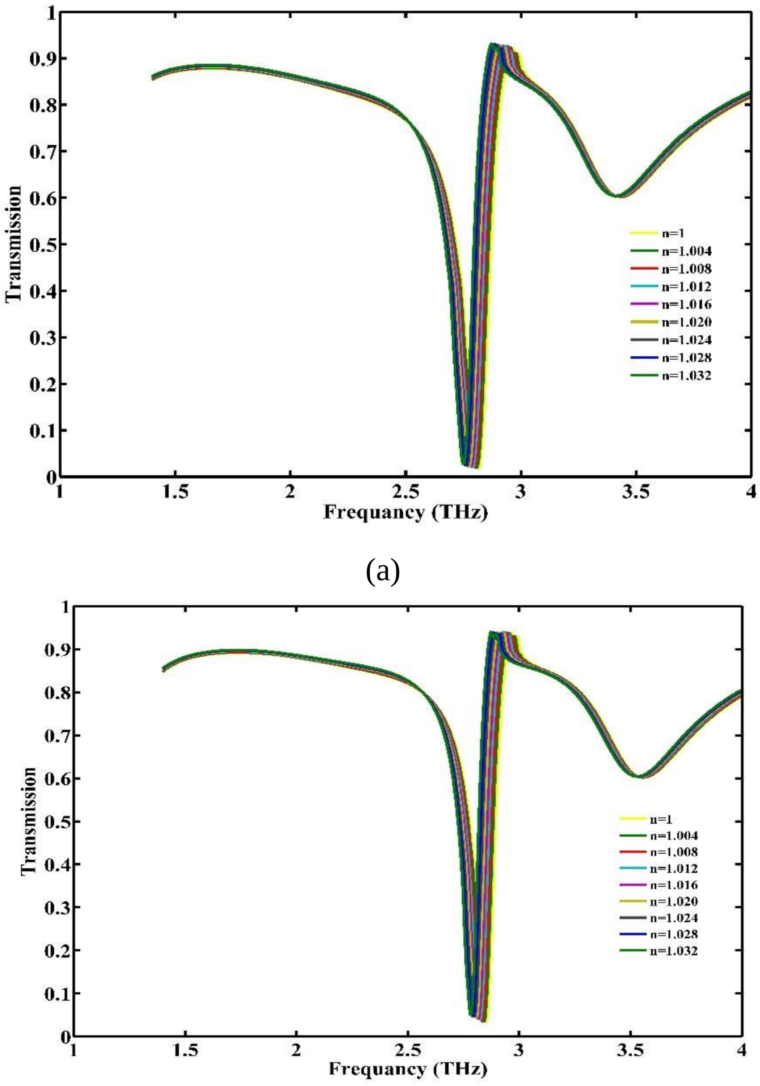
Fig. 3: Simulated transmission spectra of the metamaterial for various refractive index of sensing versus frequency. The material of substrate is Parylene-c and width of the gap is set at g=6µm.



(a) (b)

(c) (d)

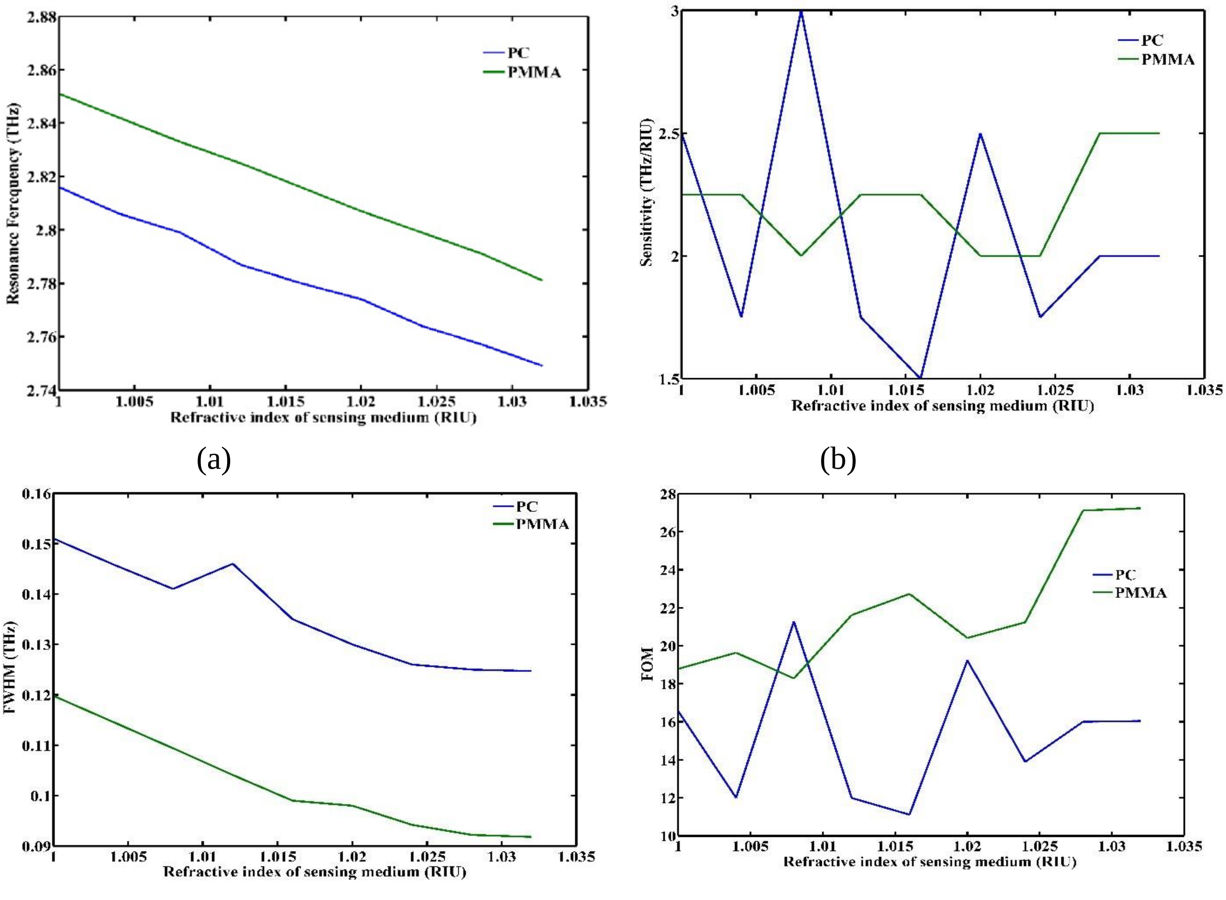
Fig. 4: The curve of (a) Changes in the resonance dip of the transmission spectrum; (b) sensitivity; (c) FWHM; (d) FOM; according to changes in the refractive index of the ambient gas. The material of substrate is PC and width of the gap is set at g=6μm.



(a)

(b)

Fig. 5: Simulated transmission spectra of the metamaterial for various refractive index of sensing versus frequency for the material of substrate is: (a) PC; (b) PMMA. The width of the gap is set at g=6μm.



(a)

(b)

(c)

(d)

Fig. 6: The curve of (a) Changes in the resonance dip of the transmission spectrum; (b) sensitivity; (c) FWHM; (d) FOM; according to changes in the refractive index of the ambient gas. The material of substrate is PC and PMMA and width of the gap is set at g=6μm.

The suggested sensor is extremely sensitive to the surrounding medium of the RI variation with sensor sensitivity that increases to 3THz/RIU (refractive index unit) while figure of merit (FOM) reaches up to 21.7 RIU^{-1} lies between 1 and 1.032 refractive index range. Moreover, the full-width-half-maximum (FWHM) was only 141 GHz. The novelty of this sensor lies in its simple design, a low-cost and highly accurate sensor device, and impressive ability to excel in gas sensing with extremely high sensitivity in the THz region. Therefore, these results provided an improved direction to design gas sensors with high FOM, low FWHM, and high sensitivity, which could meet the need for gas detection in the THz region.

Conclusions

A metal elliptical split-ring resonator in THz regime based on PC polymer substrate was proposed. The effects of changing physical parameters on sensitivity FOM, and FWHM were explored in detail in the Terahertz regime for gas sensing (refractive index range is 1 to 1.032). The change of gap had a great influence on the performance of the flexible metamaterial THz sensor. Also, the material of the polymer substrate will be effective in the sensitivity of the proposed sensor. The proposed structure on the PC substrate and with the gap width g=6μm has the highest sensitivity to the amount of 3 THz/RIU belongs to the structure, which is used for gas sensing with a refractive index of 1.008. For this refractive index sensing, the proposed sensor has an FWHM of 0.141 THz and the FOM is equal to 21.7. Therefore, this kind of flexible metamaterial sensor was more suitable for detection of certain gas concentration samples with high sensitivity and FOM and low FWHM. The structure proposed in this paper can be used as a basic structure for the design of highly sensitive gas sensors for environmental pollution monitoring in the THz region. The proposed work can also be significant in other optical sensor applications such as applications in chemical, medical and bio-sensing industries.